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(54) **Circulation pump for high purity gases at high pressures**

(57) A magnetically-driven clearance-sealed piston pump for pumping high purity gases at high pressures comprises a piston 11 having a permanent magnetic member 13 and a cylinder 2 of non-ferromagnetic material in which the piston reciprocates. The cylinder wall and piston 11 are preferably composed of metal having hexagonal close packed structure at least at the surface the coefficient of friction of said metal being less than 0.9 in air, inert gas, or ultrahigh vacuum. The metal may be alloy having the composition: 9-11% Ni, 19-21% Cr, 14-16% W, 0-3% Fe, 0.05-0.15% C, 0-1% Si, 1-2% Mn, 0-0.03% P, 0-0.03% S, and balance Co. The cylinder wall may have at least one pressure-equalising groove 17.

Movement of the member 13 is controlled and monitored by subtracting a signal representing the variable magnetic field produced by solenoid 21 from a signal representing the total magnetic field produced by solenoid 21 and member 13 to produce a signal dependent only on the position of the member 13 and controlling the variable magnetic field according to this signal.

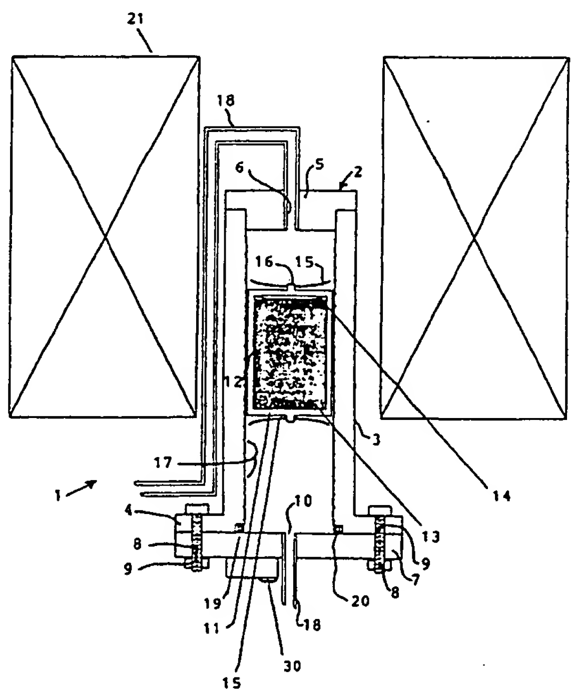

Fig. 1

GB 2 278 405 A

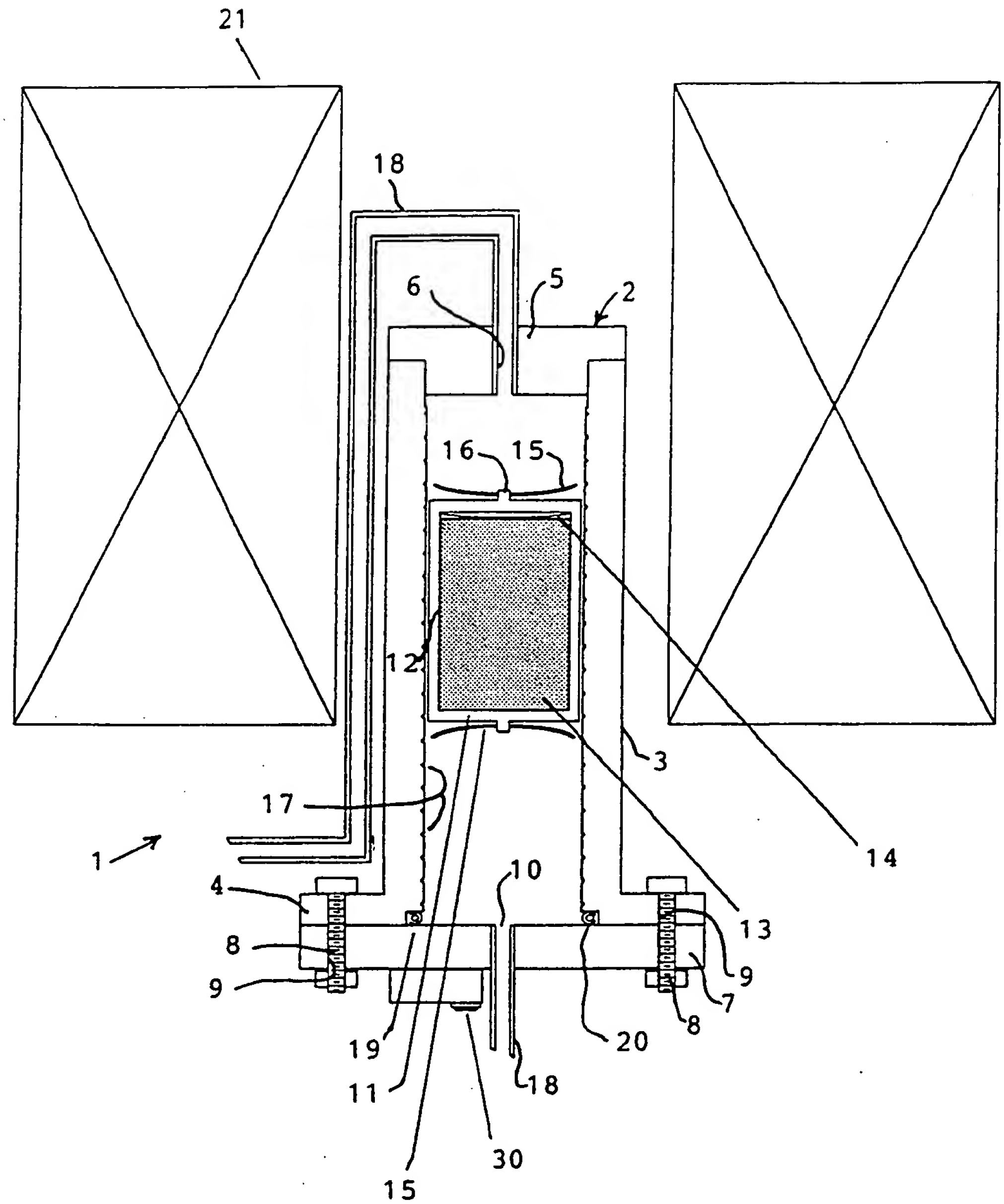

Fig. 1

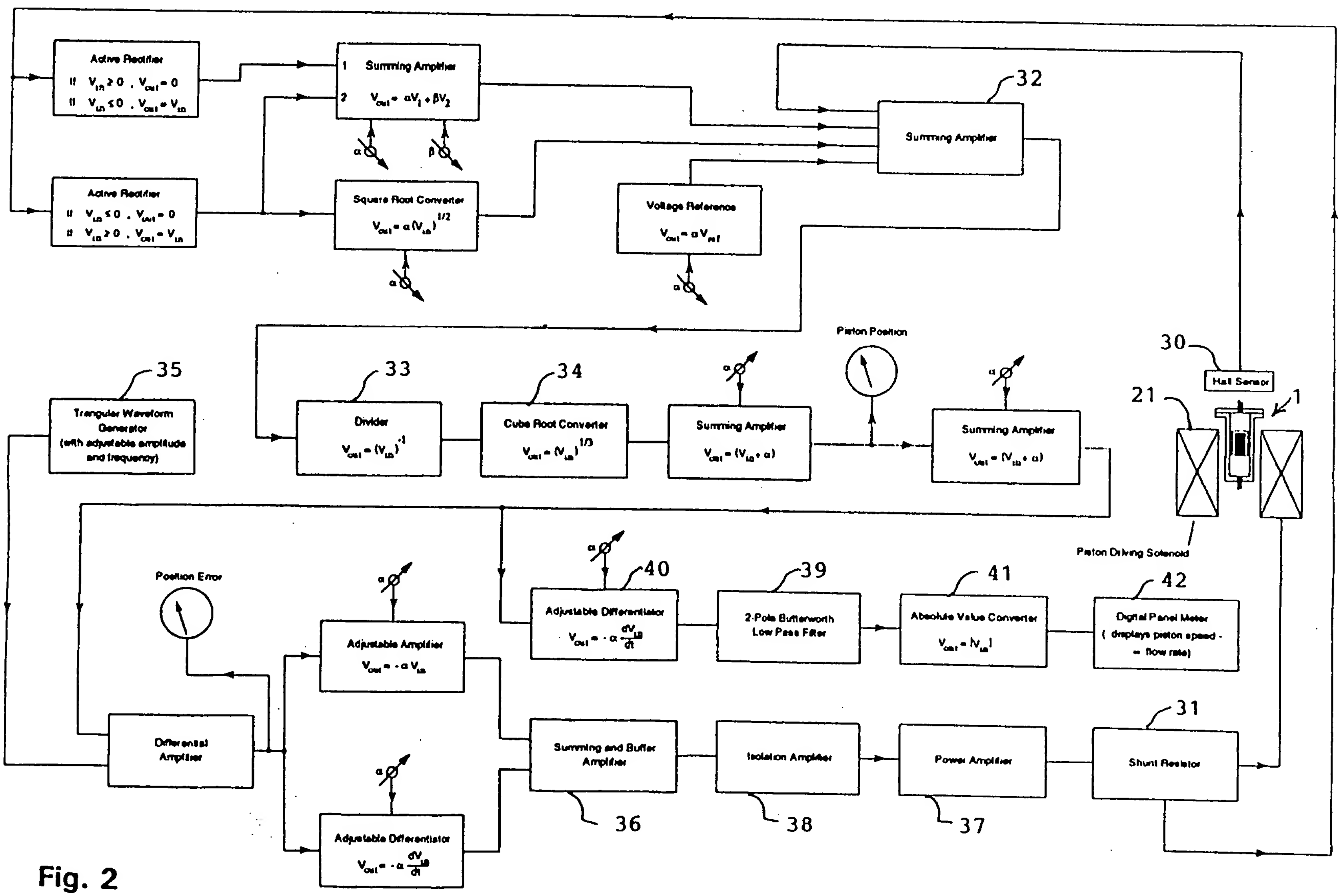
Active Rectifier
If $V_{in} \geq 0$, $V_{out} = 0$
If $V_{in} \leq 0$, $V_{out} = V_{in}$
Active Rectifier
If $V_{in} \leq 0$, $V_{out} = 0$
If $V_{in} \geq 0$, $V_{out} = V_{in}$
Summing Amplifier
$V_{out} = \alpha V_1 + \beta V_2$
Square Root Converter
$V_{out} = \alpha (V_{in})^{1/2}$
Voltage Reference
$V_{out} = \alpha V_{ref}$
32
Summing Amplifier
35
Triangular Waveform Generator (with adjustable amplitude and frequency)
33
Divider
$V_{out} = (V_{in})^{-1}$
34
Cube Root Converter
$V_{out} = (V_{in})^{1/3}$
Summing Amplifier
$V_{out} = (V_{in} + \alpha)$
Piston Position
Summing Amplifier
$V_{out} = (V_{in} + \alpha)$
30
Hall Sensor
21
1
Piston Driving Solenoid
Position Error
Differential Amplifier
Adjustable Amplifier
$V_{out} = -\alpha V_{in}$
Adjustable Differentiator
$V_{out} = -\alpha \frac{dV_{in}}{dt}$
40
Adjustable Differentiator
$V_{out} = -\alpha \frac{dV_{in}}{dt}$
39
2-Pole Butterworth Low Pass Filter
41
Absolute Value Converter
$V_{out} = |V_{in}|$
42
Digital Panel Meter (displays piston speed - ∝ flow rate)
Summing and Buffer Amplifier
36
Isolation Amplifier
38
Power Amplifier
37
31
Shunt Resistor
α
β

Fig. 2

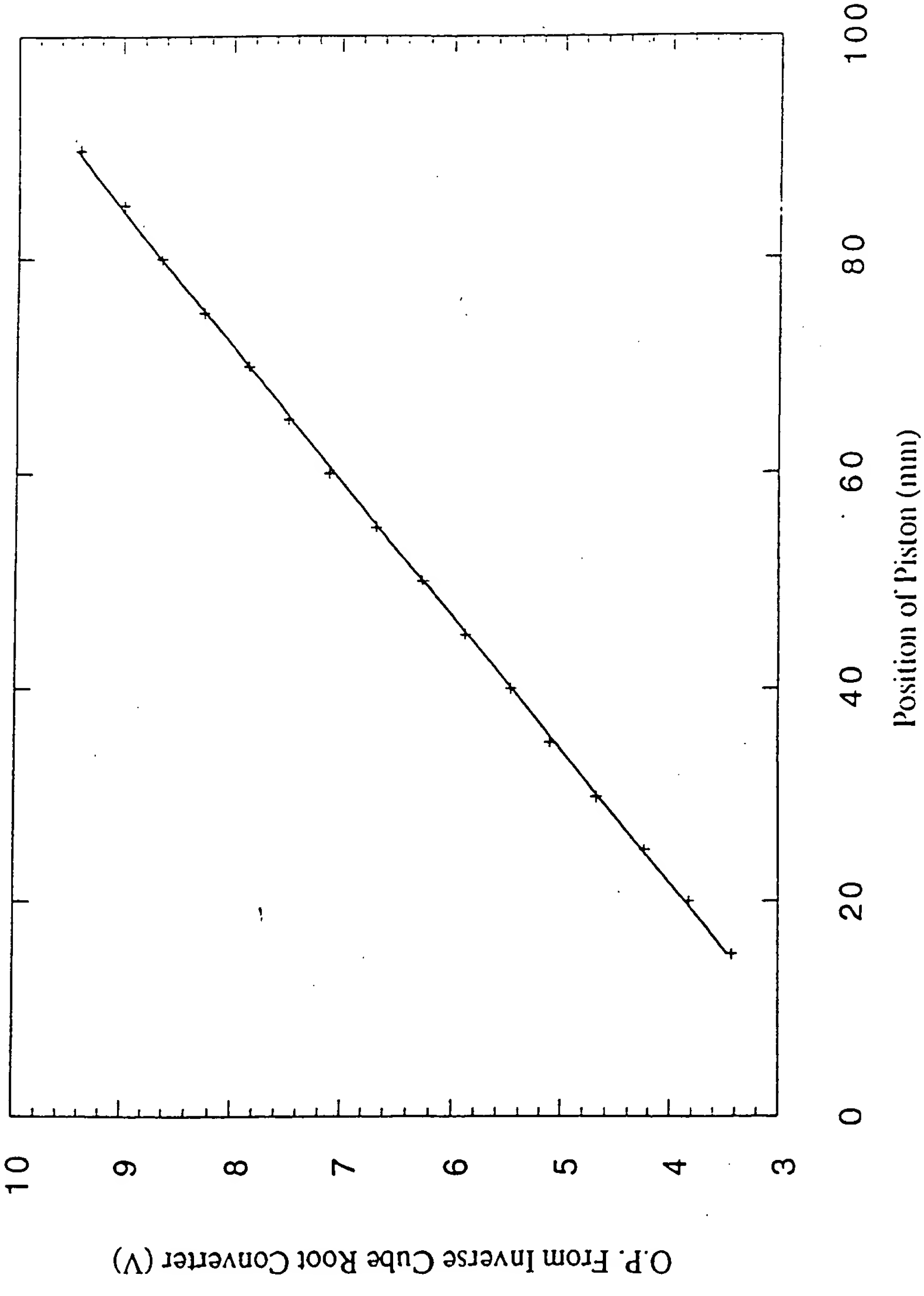
O.P. From Inverse Cube Root Converter (V)
3
4
5
6
7
8
9
10
Position of Piston (mm)
0
20
40
60
80
100

Fig. 3

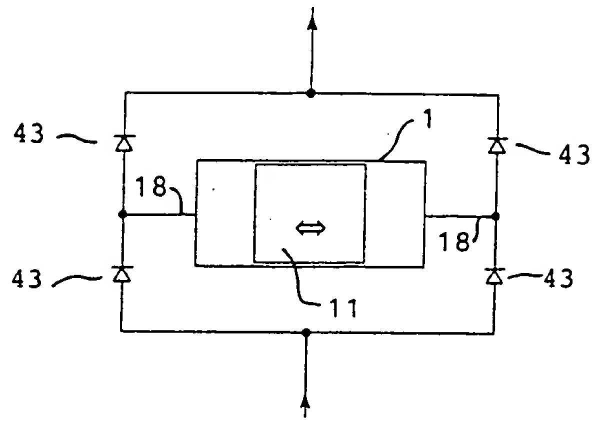

Fig. 4

Ni	Co	Cr	W	Fe	C	Si	Mn	P	S
9.00 -11.00	Balance	19.00 -21.00	14.00 -16.00	3.00*	0.05 -0.15	1.00*	1.00 -2.00	0.030*	0.030*

*Maximum

Fig. 5

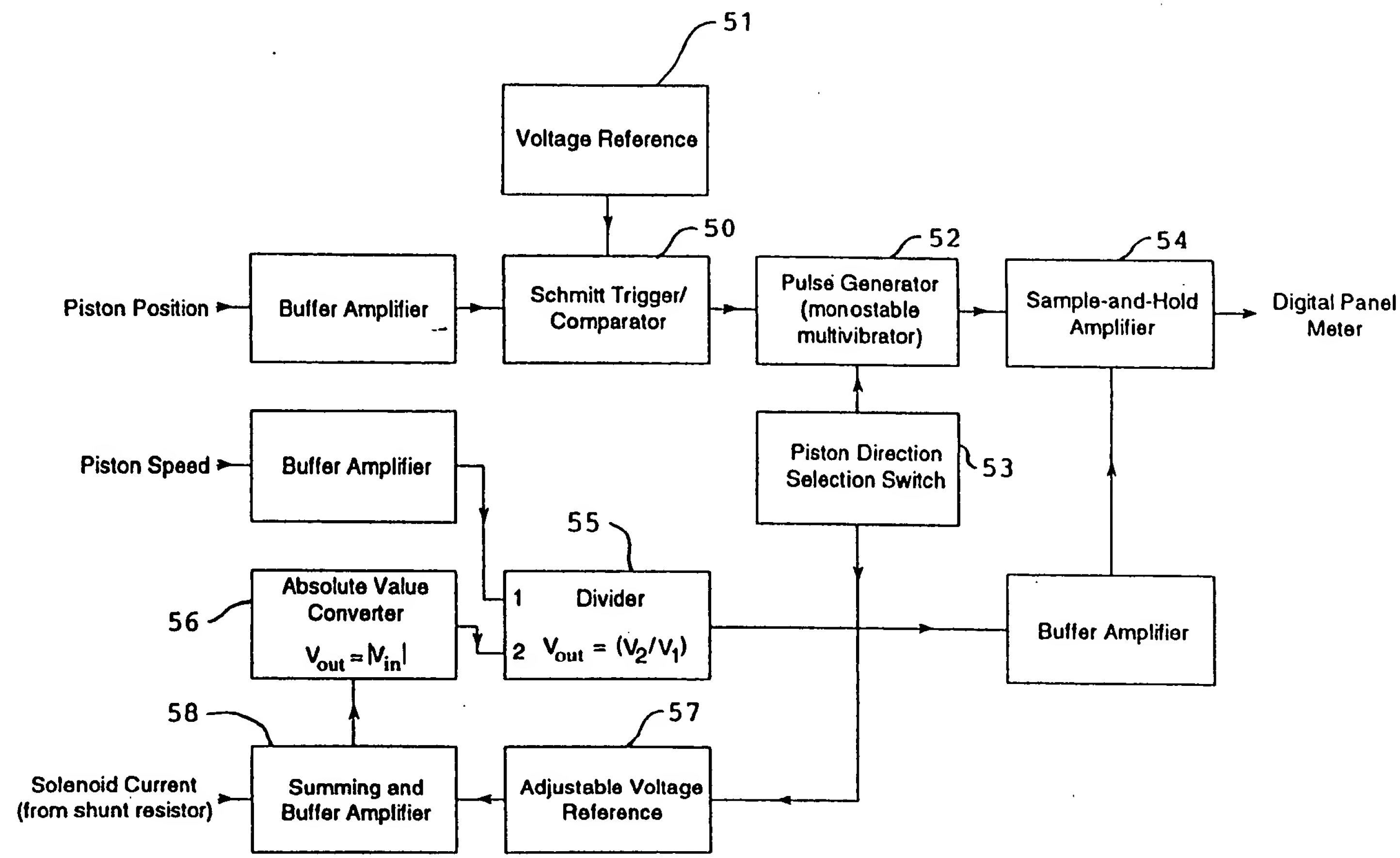
51
Voltage Reference
50
52
54
Piston Position
Buffer Amplifier
Schmitt Trigger/ Comparator
Pulse Generator (monostable multivibrator)
Sample-and-Hold Amplifier
Digital Panel Meter
Piston Speed
Buffer Amplifier
Piston Direction Selection Switch
53
55
1 Divider
2 $V_{out} = (V_2/V_1)$
Absolute Value Converter
$V_{out} = |V_{in}|$
56
Buffer Amplifier
58
57
Solenoid Current (from shunt resistor)
Summing and Buffer Amplifier
Adjustable Voltage Reference

Fig. 6

CIRCULATION PUMP FOR HIGH PURITY GASES AT HIGH PRESSURES

The present invention relates to a circulation pump for pumping high purity gases at high pressures.

High purity gases need to be circulated in a number of different processes, often at high pressures. For example, during the preparation of high purity intermetallic compounds, it is often found that one or more of the constituents has a high vapour pressure at the temperature of compound formation. Since this can lead to a loss of material through evaporation, the resulting substance may be non-stoichiometric. One very effective way of preventing this is to apply an overpressure of an inert gas, such as argon, to the materials while they are being melted. The gas tends to impede the motion of the volatile elements, so that the rate at which they escape from the melt is reduced. The method is particularly useful if the compound contains reactive elements, such as actinides or rare earths, because noble gases are almost completely inert, and hence the purity of the material can be preserved.

If the electronic properties of a compound are important, it may be desirable to keep its impurity content to the 10 ppm level, or even less. In this case, and especially if the compound contains reactive elements, the level of contamination in the gas must be extremely low. For those materials which have low vapour pressure constituents, and which can therefore be heated under vacuum without loss of stoichiometry, it has been found that the vacuum must be very high indeed if a loss of purity is to be avoided. Note that here, the word "vacuum" refers only to reactive gases such as oxygen and water vapour. The partial pressure of inert gases is irrelevant. Normally one aims for ultrahigh vacuum (UHV), which corresponds to a pressure of less than about 10^{-7} Pa ($\approx 10^{-9}$ Torr). If, however, an inert gas at atmospheric pressure is to be used in order to suppress evaporation,

the concentration of reactive impurities must be less than about 1 part in 10^{12} if their partial pressure is to be at the UHV level (say 10^{-7} Pa).

If it is assumed that an overpressure of say $2x10^{7}$ Pa (200 atmospheres) is applied, then the concentration of reactive impurities must be less than about 5 parts in 10^{15} if their partial pressure is to be in the UHV range.

Since gases are normally supplied with impurity levels of about 1 part in 10^{6} or more, extreme measures are clearly needed if the desired conditions are to be achieved. A very effective means of removing impurities involves passing the gas through some hot reactive metal, which is referred to as a "getter", but the resulting impurity levels are often on the order of 1 part in 10^{8} or more. In order to reduce this to the desired level, two main steps can be taken. Firstly, the gas can be recirculated, repeatedly if necessary. However, since gettering materials produce particles which could get carried into the materials preparation chamber, and possibly into the materials themselves, one or more filters are used. The dissociation pressures of the compounds which are formed by the contaminants and the gettering material are far lower than the UHV partial pressure levels which must be reached, so that the final partial pressure level in the preparation chamber will be limited by gas which evolves from the sample, the walls of the chamber, and the rest of the purification loop.

In order to minimise this limitation, a second step can be taken, which is to design the purification loop as one would design a vacuum system which is to attain pressures of 10^{-7} Pa ($\approx 10^{-9}$ Torr) or less. To this end, the components which make up the purification loop must be made of materials which themselves have low vapour pressures, which do not outgas, which are non-permeable to reactive atmospheric gases, and which can be baked (a process in which the components are raised to a temperature of 150°C or more under vacuum in order to rapidly drive off gases,

such as water, which have been adsorbed onto surfaces). Because of the need for vacuum baking, the class of forbidden substances must include materials which have high vapour pressures at elevated temperatures. Oils and greases must be avoided, not only because of their ability to outgas, but also because they tend to migrate. It is also desirable to minimise the outgassing of surfaces by polishing, which leads to a reduction in their total area.

The purification loop must also be free of dead and trapped volumes. Dead volumes, or stagnant regions in the gas stream, can slowly but continuously introduce contaminants into the flow and thereby prevent their rapid elimination. A trapped volume is a severe form of dead volume, and consists of an enclosed region which can vent gases into the system only through a very constricted route. Trapped volumes are problematic even in vacuum systems, in which dead volumes would not be a concern. Finally, the purification loop must be free of leaks. It might be thought that if a leak appears in the system, the gas inside will prevent the entry of atmospheric contaminants. This assumption is false, since the impurities can diffuse into the high pressure region along the walls of the orifice (within the boundary layer of the outgoing gas), or can even be sucked in by means of a venturi effect. Accordingly, the purification loop must be treated as if it were a UHV system in this regard.

In order to return the gas to the beginning of the purification loop, a pump is required. A kind which is often used to recirculate gases involves oil-lubricated reciprocating pistons or rotary vanes, and makes use of rotary seals in order to transmit motion from an external motor into the high purity environment. Such devices are completely unsuitable for the present purpose. Metal bellows pumps are made commercially which move gases without using moving seals. Unfortunately, the convolutions in the bellows produce dead volumes and regions where debris can accumulate. In addition, this

type of pump can generally be used only at pressures of up to a few atmospheres. Gas compressors are made which make use of metal diaphragms to move gases, but they often use oil to move the diaphragm and the need for oil near the purification system and the materials preparation chambers must weigh against the use of these machines. In addition, they tend to be very large, noisy and extremely expensive.

A number of magnetically driven recirculation pumps are known. Most of these designs are based on reciprocating pistons, but none of the known pumps appear to be suitable for use in the environment contemplated by the present invention. The known pumps contain dead or trapped volumes, use materials which are incompatible with UHV, or are unable to withstand bakeout. The level of outgassing from the walls of the pump is preferably no greater than 10^{-9} Pa.L.s^{-1}.cm^{-2} after bakeout of the pump, and the total leak rate is preferably no greater than 10^{-7} Pa.L.s^{-1}. More preferably, the maximum rates are respectively 10^{-10} Pa.L.s^{-1}.cm^{-2} and 10^{-8} Pa.L.s^{-1}.

In addition, many pumps are designed in such a way that the production of large amounts of wear debris seems to be inevitable. This is undesirable because small particles have a very large surface area to volume ratio, which can lead to the release of large amounts of adsorbed gas.

An object of the present invention is to overcome one or more of the problems identified above.

According to a first aspect of the present invention, there is provided a magnetically-driven clearance-sealed piston pump for pumping high purity gases at high pressures, the pump comprising:

a piston having a permanent magnetic member; and,

a cylinder of non-ferromagnetic material in which the piston reciprocally moves;

the cylinder wall and piston being composed of a metal or metals having at least some hexagonal close packed structure at least at the surface of said cylinder wall and

piston, the coefficient of friction of said metals being less than substantially 0.9 in air, inert gas, or ultrahigh vacuum environments.

Preferably, at least one of the piston and the cylinder wall is made of an alloy having a composition of substantially 9-11% Ni, 19-21% Cr, 14-16% W, 0-3% Fe, 0.05-0.15% C, 0-1% Si, 1-2% Mn, 0-0.03% P, 0-0.03% S, and balance Co.

According to a second aspect of the present invention, there is provided a magnetically-driven clearance-sealed piston pump for pumping high purity gases at high pressures, the pump comprising:

a piston having a permanent magnetic member; and,

a cylinder of non-ferromagnetic material in which the piston reciprocally moves;

at least one of the piston and the cylinder wall being made of an alloy having a composition of substantially 9-11% Ni, 19-21% Cr, 14-16% W, 0-3% Fe, 0.05-0.15% C, 0-1% Si, 1-2% Mn, 0-0.03% P, 0-0.03% S, and balance Co.

In the two aspects of the pump described above, the cylinder wall preferably has at least one circumferential pressure-equalising groove.

According to a third aspect of the present invention, there is provided a magnetically-driven clearance-sealed piston pump for pumping high purity gases at high pressures, the pump comprising:

a piston having a permanent magnetic member; and,

a cylinder of non-ferromagnetic material in which the piston reciprocally moves;

the cylinder wall having at least one circumferential pressure-equalising groove.

Preferably, at least one of the piston and the cylinder wall is made of an alloy having a composition of substantially 9-11% Ni, 19-21% Cr, 14-16% W, 0-3% Fe, 0.05-0.15% C, 0-1% Si, 1-2% Mn, 0-0.03% P, 0-0.03% S, and balance Co.

The escape of gases between the piston and the wall of the cylinder in each of the aspects described above is prevented by using a clearance seal in which the gap between the piston and the cylinder is so small that the movement of gases through it is negligible. This avoids the need for piston rings, with their need for lubrication and their tendency to create and trap debris. In addition, the small amount of gas which moves between the piston and cylinder can act as a lubricant.

Whilst the pump is for pumping gases at high pressures (of the order of $2x10^7$ Pa), it is to be understood that the pressure difference (head) produced by the pump is, in practice, much lower and may be about 0.45 to 0.75 $x10^5$ Pa.

The magnetic member is preferably a rare earth-cobalt alloy and, most preferably, a samarium-cobalt alloy.

According to a fourth aspect of the present invention, there is provided a method of controlling and monitoring movement of a movable permanent magnetic member which moves under the influence of a variable magnetic field, the method comprising the steps of:

measuring the instantaneous total magnetic field produced by the movable magnetic member and the variable magnetic field and producing a first output signal;

determining the instantaneous value of the variable magnetic field and producing a second output signal;

subtracting said second output signal from said first output signal to produce a third output signal which is dependent substantially only on the position of the movable magnetic member relative to the sensor; and,

controlling the variable magnetic field according to the third output signal.

According to a fifth aspect of the present invention, there is provided a control system for controlling and monitoring movement of a movable permanent magnetic member which moves under the influence of a variable magnetic field, the system comprising:

a sensor for measuring the instantaneous total magnetic field produced by the movable magnetic member and the variable magnetic field and producing a first output signal;

means for determining the instantaneous value of the variable magnetic field and producing a second output signal;

means for subtracting said second output signal from said first output signal to produce a third output signal which is dependent substantially only on the position of the movable magnetic member relative to the sensor; and,

means for controlling the variable magnetic field according to the third output signal.

Examples of the present invention will now be described with reference to the accompanying drawings, in which:

Fig. 1 is a cross-sectional view of a pump;

Fig. 2 is circuit diagram showing a control system;

Fig. 3 is a graph showing a measurement of piston position;

Fig. 4 is a diagram schematically showing the pump in a circuit; and,

Fig. 5 is a table showing the composition of an alloy used in an example of the pump.

A pump 1 has a cylinder 2 having a body portion 3 of circular cross-section with an integral flanged plate 4 at one, open end. At the end of the cylinder 2 opposite the flanged plate 4, the cylinder 2 is closed by an end wall 5 which has a through-aperture 6 positioned substantially centrally of the end wall 5 to provide communication with the interior of the cylinder. A cover plate 7 is fixed to the flanged plate 4 by bolts 8 which pass through bolt holes 9 provided in the cover plate 7 and flanged plate 4 to seal the cylinder 2. The cover plate 7 has a through-aperture 10 positioned substantially centrally of the cover plate 7 to provide communication with the interior of the cylinder 2.

A piston 11 is formed of a substantially cylindrical hollow shell 12 of circular cross-section which surrounds and supports a permanent magnet 13. A disc spring 14 of beryllium-copper alloy is fixed to one end of the magnet 12 to preload the magnet 13 in the shell 12 to prevent the magnet 13 from sliding back and forth in the shell 12. Although the system (which will be described in more detail below) which controls the motion of the piston is designed to prevent contact between it and the ends of the cylinder, malfunctions and human errors can take place. Therefore, the piston shell 12 is provided with a protective disc spring 15 at each end, each protective disc spring 15 being fitted using a peg 16 at each end of the shell 12, the protective disc springs 15 preventing the piston shell 12 from striking the end wall 5 of the cylinder or the cover plate 7.

In order to minimise friction between the piston 11 and cylinder 2, the pump 1 is preferably orientated in use with its axis of symmetry in the vertical direction. In practice, asymmetric gas pressures may tend to force the piston 11 against one side of the cylinder 2, with the result that a significant amount of friction is generated. This problem arises because it can be almost impossible to make the external surface of the piston shell 12 and the internal surface of the cylinder 2 perfectly even. It has been found that the resistance of the clearance gap between the piston shell 12 and the cylinder 2 to the gas leaking through it depends on the cube of the width of the gap. Consequently, even small variations may have a large effect on the pressure drop between the piston 11 and the cylinder 2. Since the pressure drop may vary on different sides of the piston 11, significant lateral forces can develop.

This is solved in the example shown by the use of a number of shallow circular pressure-equalising grooves. These may be formed circumferentially in the external wall of the piston shell 12. However, in order to avoid the creation of trapped volumes in the pump 1, it is preferred

to provide a plurality of pressure equalising grooves 17 in the interior wall of the cylinder 2, rather than in the piston. The grooves 17 are machined to a width and depth of about 250 μm, and their cross-sectional shape is approximately parabolic, in order to facilitate machining, prevent debris from piling up (as might occur, for example, in a groove of rectangular cross-section), and in order to make them easy to clean. In the specific example, twenty-two grooves 17 are provided.

The length of the cylinder 2 is such that the working stroke of the piston 11 is slightly more than twice the length of the piston 11 itself, so that every part of the interior cylinder wall is exposed to the rest of the cylinder once per cycle. Because of this, and since the outer surface of the piston 11 can exchange gas with the cylinder wall and its grooves 17, the prolonged outgassing which may be associated with trapped volumes is avoided.

Several model piston-cylinder combinations were created in order to allow the effectiveness of the pressure equalising grooves 17 to be determined. Each piston and cylinder was honed to the highest possible tolerances in order to eliminate uncertainties due to machining errors. To carry out the test, each piston was placed into a cylinder so that it protruded about 0.5 cm above the top. It was then spun, and allowed to descend under its own weight. It was found that all the pistons were able to complete several tens of revolutions while descending through the grooved cylinder, while none of the pistons were able to complete more than one or two revolutions while descending through the plain cylinder.

In clearance sealed pumps, wear is a concern not only because of its possible effect on structural integrity, or because of the gases which debris may produce, but also because even small amounts of wear will adversely affect the performance of the seal. Although grooving the wall of the cylinder 2 should reduce the amount of friction which takes place when the piston runs through it, the materials

of the piston shell 12 and/or of the cylinder 2 should be carefully selected to minimise or substantially eliminate wear. It is difficult to find materials which are strong, clean (in the UHV sense), non-ferromagnetic, and wear resistant in a vacuum or inert gas at ambient temperatures. Regarding the latter, many metals, and particularly those metals with a cubic crystal structure, tend to cold weld if they are rubbed together in an environment which does not encourage the formation of contaminated surface layers. It is these layers (which may take the form of oxides) which prevent metallic bonding from taking place. Since bonding is a source of wear in metals, alloys with this type of crystal structure, such as the austenitic stainless steels, tend to be susceptible to it. Since the piston 11 in the recirculation pump will be moving back and forth in an atmosphere containing virtually no reactive gases, protective layers will not form, and any existing layers will be removed by friction and outgassing. Consequently, the wear on the piston and cylinder may be severe unless they are made of suitable materials.

Metals which have a hexagonal crystal structure, such as zinc and cobalt, seem to have much more favourable wear properties than the cubic metals. Samples of cobalt which have been cleaned of surface contaminants in ultra high vacuum will not seize when they are rubbed together, and can in fact display a relatively low coefficient of friction (≈ 0.4). In contrast with most metals, the friction coefficient of cobalt against itself decreases when surface oxides are removed. In comparison, a typical bearing steel may exhibit a friction coefficient of 0.5 when it slides against itself in air at room temperature, but welds when the same thing occurs in a sufficiently high vacuum.

The present inventor has located a commercial cobalt alloy (Haynes 25 {Trade Mark} (L-605) produced by Haynes International, Inc.) which is clean, tough, non-ferromagnetic (with a permeability of less than 1.00), and

which has been formulated in such a way as to enhance its resistance to wear. The alloy Haynes 25 has a chemical composition as set in the table in Fig. 5, in which the percentages of various elements in the alloy are identified.

Haynes 25 has a face centred cubic crystal structure. However, the FCC lattice near the surface of the material transforms at least partially to a HCP one during sliding contact, as will occur when the pump 1 is used. The material is wrought (unlike some other cobalt-base wear resistant alloys, which may be cast or sintered). Consequently, the outgassing which can take place from pores in these materials should be absent. Haynes 25 also has the advantage of having a high tensile strength (approximately twice that of the austenitic stainless steels at room temperature) and a large Youngs modulus (approximately 14% greater than that of the austenitic stainless steels). It is also highly resistant to corrosion. The material is very difficult to machine, but it is possible to drill and turn this material using ordinary high speed steel tools, although carbide or cobalt alloy tools are very much more effective. Because of the excellent properties of this type of cobalt alloy, and in particular because of the wear resistance which it can be expected to exhibit in the presence of very high purity inert gases, it is preferably used to make the cylinder 2 and the outer shell 12 of the piston 11.

The first operation in making the device is to fabricate the main body of the cylinder 2, its end wall 5, and its lower cover plate 7. The outside of the cylinder 2 is machined to its final dimensions and the inside is nearly machined to its final dimensions. Sharp corners are avoided wherever possible in order to prevent the creation of stress risers. A stress-relieving operation is then undertaken by heating all parts to 1200°C in a vacuum furnace. The purpose of this is to remove any residual stresses which may be produced by machining and which may

cause irregularities to form in the gap between the piston and cylinder. Vacuum heating also serves to remove dissolved gases from the metal, which results in a reduction of outgassing.

The pressure equalising grooves 17 are then cut on the inside wall. The cylinder is then honed to a roundness of 1 μm. Following this, the end wall 5 of the cylinder 2 is attached to the cylinder itself by vacuum brazing using a cobalt-base alloy which is made by the American company Wall Colmonoy under the name "Nicrobraze 210". This material is UHV compatible and has a similar composition to the parent metal. It is also non-ferromagnetic. Austenitic stainless steel gas feed tubes 18 are electron beam-welded respectively to the end wall 5 of the cylinder 2 and the cover plate 7, the gas feed tubes 18 being respectively in communication with the through apertures in the end wall 5 and the cover plate 7. Finally, the inside of the cylinder 2 is lightly honed and polished again, honing being facilitated by the provision of a small depression machined into the top inside surface of the cylinder.

Although electropolishing is generally preferred to mechanical polishing in the preparation of surfaces which are to be exposed to vacuum, the situation must be reexamined in light of the present requirements. Mechanical polishing results in the formation of a disturbed surface layer which, as we have seen, appears to play an important role in the wear resistance of Haynes 25. It is known that electropolishing removes such layers, and it might therefore be expected that the use of this method would render the surfaces of the piston and cylinder susceptible to damage until the sliding contact between them formed a new surface layer. Accordingly, mechanical polishing is used as the final step in preparing the surfaces. Since the inside surfaces of the gas feed tubes 18 are not exposed to sliding contact, they are electropolished.

In the present pump 1, the seal between the end of the cylinder 2 and the cover plate 7 is made with a metal seal 19. The preferred form of the seal 19 is a device manufactured by the French company Cefilac under the trade name "Helicoflex". The "Helicoflex" seal is an all-metal arrangement which is completely UHV compatible, capable of operating at pressures ranging from 10^{-8} Pa ($\approx 10^{-10}$ Torr) to 10^{8} Pa with a leak rate of less than about 10^{-7} $Pa.L.s^{-1}$, and able to withstand temperatures of up to 700°C. Special "Helicoflex" seals are available with leak rates of less than $10^{-8}Pa.L.s^{-1}$ if required. In addition, all the materials which make up a "Helicoflex" seal are non-ferromagnetic. For the purposes of carrying out tests, the "Helicoflex" seal can be replaced by an ordinary elastomer O-ring. Note that those parts of the cylinder 2 and the cover plate 7 which make contact with the "Helicoflex" seal 19 must not be polished, because a certain level of surface roughness is necessary in order to produce a seal. A radial slot (not shown) is machined into the top of the cover plate 7, from its outer diameter to the outer diameter of the depression 20 which contains the "Helicoflex" seal 19, in order to facilitate mass spectrometer leak detection.

The gas feed tubes 18 are terminated with either ordinary VCR (Trade Mark) couplings or "S" type VCR (Trade Mark) face seal fittings. These devices, which are fairly standard couplings for joining high purity gas lines, are manufactured by the American Cajon Company. They are UHV compatible, bakeable and non-ferromagnetic. Although the VCR fittings and feed tubes limit the maximum operating pressure to about 350 atmospheres, the pump could in principle be used at 1000 atmospheres if "Helicoflex" seals and higher pressure tubes were used.

The choice of material for the permanent magnet 13 in the piston 11 is quite important. The material should withstand temperatures of at least 150° C without appreciable losses of magnetisation, in order to allow the

pump to be baked out. It should preferably have a straight line demagnetising characteristic and a high coercive force, because it does not form part of a closed magnetic circuit (i.e. it has no "keeper") which would otherwise prevent losses of magnetisation due to external fields or internal demagnetising fields (since the ratio of magnet length to diameter is relatively small in the present case (about 1.4:1), the internal demagnetising field is particularly significant). It should preferably have a high remanence combined with a differential permeability which is close to unity over a large range of applied fields both with and against the direction of magnetisation (for reasons which will be made clear shortly). Finally, it should preferably have a high energy density product, in order to make it possible to exert a large force on the piston 11 for a given volume of magnet material and for a given magnetic field gradient.

Samarium-cobalt has been found to have all of these desired properties, although other rare earth-cobalt alloys may be suitable. The material chosen for the magnet is a samarium-cobalt alloy which has an energy density product of up to 28 MGOe, a coercive force of up to 10,400 Oe, and a maximum operating temperature (up to 350° C) which is sufficiently high to enable it to withstand normal bakeout temperatures. The demagnetising characteristic is practically a straight line from zero demagnetising field all the way to the coercive force of the material. Furthermore, the material has a high remanence (up to about 10.8 kG) and the differential permeability is close to unity over an applied field range of many kilogauss both with and against the direction of magnetisation (or, in other words, the changes which take place in the magnetization are small compared with the zero applied field magnetization in usefully large applied fields both with and against the direction of magnetization).

In forming the shell 12 of the piston 11, th inside is machined to its final dimensions and the outside is

nearly machined to its final dimensions. Before the magnet 13 and disc preload spring 14 are loaded into the shell 12, the latter is stress relieved in the same way as the cylinder 2. The magnetisation direction of the magnet 13 is aligned with the symmetry axis of the piston shell 12 and cylinder 2. The magnet 13 and disc spring 14 are encapsulated into the shell 12 using electron beam welding. The creation of a gas-tight seal is necessary because the samarium-cobalt magnet material is a sintered substance which is not UHV compatible. The use of electron beam welding has advantages over other bonding methods in several respects. It does not heat up the piston assembly (unlike, for example, vacuum brazing) and therefore will not damage the magnet. In fact, it heats only a very small part of the piston around the join, and in this way also minimises the distortion which might otherwise occur (if, for example, arc welding were used). The lack of distortion is important because of the very small gap between the piston and the cylinder. The electron beam is affected by the field which is produced by the magnet, but adjustments can be made in order to compensate for this. The method is also intrinsically very clean, because it takes place in a vacuum. Laser welding is another possible way of carrying out this operation.

After the magnet 13 and disc spring 14 have been welded into the shell 12, the piston 11 is turned, honed and polished to fit the cylinder 2. The final clearance gap between the piston and cylinder is preferably less than about 0.023 mm; more preferably, the gap is less than about 0.011 mm; most preferably, the gap is substantially 5 μm.

The detection of leaks between the inside and outside of the piston presents a slightly unusual problem, because there is no way of gaining access to the inside once it has been sealed off. One solution involves a method which is sometimes referred to as "bombing". This involves placing the piston in a high pressure chamber, which is then filled with helium at about 2×10^7 Pa. If the piston has any

leaks, the helium will pass through them and fill up the voids which exist between the magnet, the disc spring, and the inside wall of the piston shell. The piston is then removed from the chamber, and placed in a vacuum vessel which has been connected to a mass spectrometer leak detector. Any helium which has accumulated in the piston will move through the leaks in the other direction, and trigger a response from the leak detector. Although the piston may have to be completely remade if any leaks were found, it is unlikely that this will be necessary, because electron beam welding is a very reliable process.

A cylindrical solenoid 21 of annular cross-section is provided for driving the piston 11. The solenoid 21 consists of 1352 turns of flat copper wire which are wound onto a nonferromagnetic stainless steel bobbin (not shown). The insulation on the wire is enamel (a relatively low temperature insulation), so that the solenoid must be removed from the pump prior to bakeout. However, if a polyimide insulation were used, this would not be necessary, since such materials are capable of withstanding temperatures of up to 240° C. The dimensions of the bobbin were chosen so as to allow the solenoid to produce the greatest possible magnetic field at its centre for a given power input. In particular, if R_i is the inner radius of the solenoid coil, R_o is the outside radius and L its length, it can be shown that the highest possible magnetic field for a given power input exists in the centre of the coil if $(R_o/R_i)=3$ and $(L/R_i)=4$. Consequently, this design produces a large average field gradient, which is also relatively uniform over the length of the cylinder 2. As a result, since the force which acts on the piston is proportional to the field gradient, a large and fairly constant force can be exerted on the piston over the full length of its travel.

The advantage of this design can be put more precisely. The integral of the field gradient along the symmetry axis of the solenoid up to its centre gives the

field at the centre, and the integral of the force which acts on the piston as it is brought along the symmetry axis of the solenoid up to the centre is equal to the total amount of work which is done on it. Consequently, this solenoid configuration permits the largest amount of work to be done on the piston for a given power dissipation in the solenoid. In the present case, with a 22 MGOe magnet, the maximum force which acts on the piston amounts to between 20 and 33 N along the length of the cylinder at a solenoid current of 15 A. The resulting differential gas pressure is between about 0.45 and 0.75 atmospheres. The use of a samarium-cobalt alloy with a energy density product of 28 MGOe can bring the pressure range up to between 0.53 and 0.87 atmospheres.

It is important to avoid having the piston 11 strike the end wall 5 or the cover plate 7, or at least to prevent it from doing so with its maximum velocity, as this could result in damage to the magnet and the possible generation of wear debris (the samarium-cobalt material is very brittle, and the impact velocity could be as high as several tens of centimetres per second), and cracks may be generated in the cylinder. Since the pump will operate at pressures of 200 atmospheres or even higher, this would obviously be a very dangerous situation. This is partly alleviated by the use of the protective springs 15 on the upper and lower surfaces of the piston shell 12.

Also, the impact of the piston against the cylinder would also produce vibrations which are detrimental to certain materials preparation operations, such as Czochralski crystal growth and float zone melting.

Furthermore, it is desirable to ensure that every part of the cylinder wall is exposed to the rest of the cylinder at regular intervals, as mentioned above.

It is also desirable to control the instantaneous flow rate. The piston accelerates along the cylinder in a way which depends on the gas composition and pressure, the flow impedances which are present in the system, the position of

the piston in the cylinder, whether the piston is moving with or against gravity, friction between the piston and the cylinder, and the solenoid current. Of these, only the latter can be adjusted arbitrarily. Since in prior art systems, the current is in either one of two states, the only way of adjusting the flow rate was to vary the timing of the current pulses. However, this only affects the average flow. When the piston moves, it invariably does so quite rapidly. Nevertheless, it may spend a considerable fraction of its time at rest at one end of the cylinder (waiting for the solenoid current to change), during which no flow takes place. It is very difficult to correct for these deficiencies by adjusting the size of the current pulses as well as their timing, especially if one wants to obtain low flow rates.

Furthermore, the gas in the materials preparation chamber may not be continuously replenished. Also, the quick movement of the piston can cause needless evaporation of material, since it is known that the rapid flow of gas past a sample will increase it evaporation rate. Finally, the manufacturers of gettering purifiers normally recommend restricting the flow rate to some value in order to achieve a given gas purity and the makers of particle filters specify a particular flow rate in order to ensure the removal of a given fraction of the particles in the gas stream. Although recirculation of the gas should allow high purity levels to be reached regardless of the amount of purification which takes place on each pass (depending on the level of outgassing in the system), control of the speed of the piston should make it possible to estimate the purity of the gas after a given recirculation time. It should also allow the establishment of conditions which can be reproduced during different materials preparation runs.

The present invention also provides a system which is able to monitor and control the motion of the piston without sacrificing any of the advantages associated with this type of pump. This makes it possible to reduce wear

of the pump and its associated check valves, prevent damage to the magnet, eliminate vibration and noise, ensure that every part of the cylinder wall is exposed to the rest of the cylinder once per cycle, and ensure that the instantaneous flow rate of the gas has the desired value (the minimum flow rate will be determined by the leakage of gas past the piston; the range of possible flow rates which the present system will allow is greater than 100:1). It also provides a means of monitoring the gas flow rate which is independent of gas composition and pressure. Finally, the solenoid current which is required in order to move the piston at a given speed when it is moving in a certain direction at a particular position in the cylinder is proportional to the back-pressure which it must overcome. Since increases in the back-pressure are likely to come mainly from clogging up of the particle filters or because the getters have been completely reacted with impurities, the arrangement provides a means of continuously monitoring the status of these devices. This scheme involves monitoring the position of the piston electronically, and then using this information to control the current passing through the solenoid, as will be discussed in detail below and later.

The arrangement is as shown in Fig. 2. A Hall sensor 30 (shown also in Fig. 1) is fixed to the cover plate 7 and senses the total magnetic field which results from the combination of the fields produced by the piston magnet 13 and the solenoid 21. This is where the high remanence and near-unity differential permeability of the magnet material are particularly useful, as well as the fact that all of the materials which make up the pump (except the magnet) are non-ferromagnetic, as it means that the total magnetic field is, to a very good approximation, a linear combination of the fields produced by the solenoid 21 and the magnet 13. Therefore, if the field which is produced by the solenoid 21 is known, it is possible to determine the field which is produced by the magnet 13 in the absence

of the solenoid field by a simple subtraction. The field which is produced by the solenoid 21 can be determined by measuring its current, since the two are proportional. The voltage which is produced by the Hall sensor 30 is a fairly linear function of the total field (deviations from linearity can be corrected, as will be described shortly).

As shown in Fig. 2, the solenoid current is determined by measuring the voltage across a resistor 31 which is placed in series with the solenoid 21. This is scaled (using components indicated in Fig. 2), and subtracted from the voltage produced by the Hall sensor in a summing amplifier 32. Since the Hall sensor voltage is not quite a linear function of field, the scaling coefficients for the solenoid field are made to depend on the direction of the field. It is also desirable, for one of the field directions, to add an ad-hoc correction to the total which is proportional to the square-root of the solenoid field. These corrections are most important when the piston 11 is furthest away from the Hall sensor 30, and hence when the magnet field is a small fraction (possibly less than 5%) of the solenoid field. It turns out that the output voltage from the Hall sensor 30 is offset from zero, so a constant voltage is added to the others in order to make the total strictly proportional to the magnet field. Since small variations in the output from the Hall sensor 30 could be important (depending on the position of the piston 11) a precision voltage reference is used to supply the required level.

The result of these calculations is a voltage which is dependent only on the position of the piston magnet 13, and independent of the size of the solenoid field. What one would like to do with this information is to use it in conjunction with a servo-controller to force the piston position to have the desired time dependence. For this purpose, the aforementioned voltage should be a linear function of the piston position. Instead, it is a highly nonlinear function of this quantity. However, it turns out

that the position dependence of the magnet field follows very closely the law which holds for a point magnetic dipole, which is that the field of a dipole at a given point in space is inversely proportional to the cube of the distance r between the point and the dipole itself. This law holds very well for the magnet which is used in the piston, and for the possible range of distances between the piston and the Hall sensor (from about 3 to 8 cm). This is somewhat surprising, since the dimensions of the magnet are relatively large compared with these values. The result can be exploited to linearise the relationship between the piston position and the voltage which is proportional to the magnet field.

Referring once again to the Fig. 2, the signal from the summing amplifier 32 is fed into a circuit 33 which generates an output voltage which is proportional to the inverse of the input voltage, and from there into another circuit 34 which generates an output voltage proportional to the cube root of the input voltage (devices which carry out such operations are available commercially in the form of modules). The result of this transformation is shown in the graph in Fig. 3, which shows the output voltage plotted against the piston position for a number of different positions, and the best straight line fit to these points.

With the resulting linearised signal, it is possible to implement closed loop control of the piston position. This is done by subtracting the piston position signal from a reference signal which is generated by an oscillator 35. Since it is desirable that the flow rate be as constant as possible, the shape of the reference waveform from the oscillator 35 is triangular. The error voltage is amplified, and added to a scaled version of its time derivative by a summing and buffer amplifier 36. The resulting signal drives a power amplifier 37 which supplies current to the solenoid 21. In order to prevent the possibility of dangerous currents flowing from the shunt resistor 31 back to the power amplifier 37 through the

control circuit, the galvanic loop is broken by means of an isolation amplifier 38. This control scheme is known as a proportional-differential servo system. The speed of the piston can be changed by adjusting the amplitude or frequency of the reference signal. It is preferable to adjust the frequency, because the amplitude should always be large enough to allow every part of the cylinder wall to be exposed once per cycle. In addition, it must be limited in order to prevent the piston from coming into contact with the ends of the cylinder. In this way, the instantaneous gas flow rate can be varied over a wide range without damaging the magnet or the ends of the cylinder, regardless of changes in gas pressure or flow impedance. The vibrations which this arrangement produces are very small, because the piston is always supported by a magnetic field. Any disturbances which may be generated by the reversal of the piston motion at each end of its travel can be eliminated by reducing the piston speed, reducing the gain of the servo controller, or by using a reference waveform which has a limited second time derivative (such a sine wave). The system also ensures that every part of the cylinder wall is exposed to the rest of the cylinder once per cycle.

The absolute value of the time derivative of the linearised piston position signal provides a direct indication of the gas flow rate, independent of the type of gas or its pressure. The signal is sent through a low pass filter 39 after differentiation in an adjustable differentiator 40, but before the absolute value is taken in a converter 41, in order to prevent noise from being rectified and appearing as piston motion. It has been found that if the flow rate signal is sent to a LED-based digital panel meter 42 for display, high frequency noise from the meter can travel back down the line, couple into the flow rate circuit, and appear at its output as a dc level, which is interpreted as piston motion. This can be

prevented by the installation of a 0.1 μF bypass capacitor across the output terminals of the circuit.

Although all the monitoring and control functions which have been described are carried out by analogue electronics, they could also be carried out by a digital computer. Analogue circuitry can make the required functions cheaper and easier to implement than if digital electronics were used. On the other hand, this will not always be the case, and if it were desirable to improve the accuracy of the piston position detection arrangement (for example, by accounting for deviations from the $1/r^3$ dipole field law), or to increase the effective gain of the servo controller, then a digital approach may be necessary.

The selection of the Hall sensor 30 is fairly important, since most commercial devices have a very strong temperature dependence. This can result in substantial errors in the apparent position of the piston 11 when the distance between it and the sensor 30 is large. The device used in a particular embodiment comes in the form of a module which contains the Hall element and an amplifier, and has an unusually low sensitivity to temperature variations. It is made by the American company Honeywell Microswitch and has the part number SS94A1. Although the Hall sensor 30 should in principle have a symmetrical field response, in practice one finds that the linearity of the device is much improved if it has a particular orientation with respect to that of the magnet.

The dimensions of the wire used to wind the solenoid can be chosen so that the solenoid could be impedance matched to a commercial audio amplifier, which are inexpensive and capable of delivering large amounts of power. In order to maximise the current density inside the solenoid (and thereby produce the largest field for a given amount of power, and hence field gradient, piston force, and gas pressure, using a given power supply) wire with a rectangular (as opposed to circular) cross-section was selected. The resistance of the solenoid is 2.0 ohms and,

with the chosen amplifier, it is possible to pass a current of at least 15 A through it for long periods of time. Although these amplifiers are normally designed to amplify ac signals, a simple modification makes it possible for them to work at dc. If large amounts of power are to be dissipated, it is desirable that the solenoid be constructed in such a way that heat can easily escape from its windings. This can be done by giving its support bobbin an open structure, in order to encourage convection. Further measures might involve producing small annular gaps between the windings with the aid of plastic spacers in order to permit the flow of air, and placing a cooling fan on top of the solenoid in order to produced forced convection.

In order to ensure that the flow of gas in the purifier is unidirectional, one-way valves ("check valves") 43 are used to rectify the motion which is produced by the pump 1, as shown in Fig. 4. The scheme amounts to a form of bridge rectification, which forces gas to flow in the desired direction regardless of the direction in which the piston 11 is moving. In order to ensure that only a small fraction of the pressure which is produced by the pump is discarded in opening the check valve 43, it is desirable to use a valve which has a low opening (or "cracking") pressure. On the other hand, the cracking pressure should not be so low that the valve cannot seal properly. A very low cracking pressure (0.04 atmospheres) is preferred for the check valves 43.

Whilst, on the whole, it is best to use metal-to-metal seals (and, consequently, large sealing forces), the seal used for the check valves 43 is formed by a perfluoroelastomer, which is marketed by E.I. DuPont de Nemours & Co. under the trade name "Kalrez". This material has excellent outgassing properties compared with other elastomers. It can be baked at 300°C and has an initial outgassing rate which is only 3-5 times that of stainless steel at this temperature. It is not necessary for the

seal to be lubricated in this application, so that the hazards which are posed by oils and greases are absent. Unfortunately, the diffusion rates of gases across Kalrez are rather high, which means that, although it is suitable for seals which separate different internal sections of the purification system, it is not suitable for those which separate the inside of the purification system from the outside.

If the properties of Kalrez-sealed check valves are inadequate, then it is possible to use all metal solenoid valves which are operated by the square wave which is generated in the process of producing the reference waveform. This method would have the advantage of eliminating check valve backpressure, at the expense of greater complexity. In this case, of course, care would have to be taken to ensure that the seals have the required properties. Wear in such a valve could be minimised by using a pair of diaphragms to hold the valve stem. This would make it possible to hold the stem in the correct position and orientation with respect to the valve seat, while allowing the stem tip to be moved towards and away from the seat without sliding friction. The pair of diaphragms would also act as a restoring spring.

Although the tolerances of the moving parts in the check valves are not so stringent as they are for those in the pump, and since the amount of relative movement which they undergo is very much less, it might be desirable to use a wear resistant alloy, such as Haynes 25, for them as well.

It is desirable to monitor for when the getter or getters, which remove impurities (i.e. reactive gas molecules as opposed to macroscopic dust particles which are removed by filters), reach the end of their useful life due to their being completely reacted with the impurities. It has been found that monitoring the pressure drop across a getter is a reliable and accurate method of determining the state of the getter. Similarly, monitoring the

pressure across a particle filter can also provide an indication of when the filter is clogged.

This can be done by using the normal outputs of the pump control system described above, which eliminates the need for pressure gauges (which are unlikely to be sensitive enough at the high pressures of say 200 bar contemplated by the present invention or which would be unable to withstand such pressures). The solenoid current can be used to determine the force acting on the piston, and hence the pressure drop across the pump. In doing this, one must allow for the force of gravity acting on the piston, and the check valve backpressures (if spring-loaded, rather than solenoid-actuated, check valves are being used). Since the solenoid field gradient is not uniform along the cylinder, and since somewhat complicated behaviour occurs at the ends of travel (where the piston reverses direction and the check valves change state), it is desirable that measurements of solenoid current take place when the piston is at a well defined and consistent position somewhere in the middle of the cylinder.

This may be done by an arrangement which monitors the piston position and continuously compares it with a reference. When the piston, moving in a given direction, passes the position indicated by the reference, a signal is produced which causes the value of the voltage proportional to the pressure drop to be measured by a sampling circuit. This value is then presented on a display until the piston passes the same position in the same direction, at which time the reading is updated.

The voltage corresponding to the pressure drop is determined by an arrangement which simultaneously measures the solenoid current and the piston speed and continuously forms a quotient with these two quantities. This quotient, which is linearly related to the force acting on the piston (which is in turn linearly related to the pressure drop) divided by the gas flow rate, represents a flow resistance. It has the advantage (over a signal linearly related to the

solenoid current alone) of being dependent only on the state of the getter and independent of piston speed. It is a meaningful quantity for an ideal incompressible gas, in conditions under which the flow of gas through the system is dominated by viscous forces. The inert gases which are used in materials preparation can be considered ideal, and can be considered incompressible if the pressure drops throughout the purification loop are small compared with the absolute pressure. One must also make sure that the speed of the piston is high enough that gas leakage between it and the wall of the cylinder is small compared with the desired gas flow. Constant forces (e.g. that due to gravity on the piston) can be accounted for by adding a constant to the solenoid current signal before the quotient is formed. The force of gravity acts in one direction only, so that the signal which corrects for it is constant. However, the force which must act on the piston in order to keep the check valves open (for spring-loaded check valves) depends on the direction of motion of the piston, so that the corresponding correction signal must change. This fact would not be an issue if one were content to measure the gas flow resistance for one direction of piston movement only. However, measurement for both directions makes it possible to determine the status of the check valves (e.g. for leakages and seizures) by comparing the extra flow resistance produced by one set (two out of a total of four) against that of the other, since it is very unlikely that exactly the same defects will occur simultaneously in both sets. Consequently, the value of the added constant is made to depend on the direction of piston movement for which the measurement is taken.

In Fig. 6, a Schmitt trigger/comparator 50 measures the difference between a voltage which is indicative of the piston position (produced by the arrangement shown in Fig. 2) and a reference voltage provided by a reference voltage source 51. A monostable multivibrator 52 monitors the output of the comparator, and produces a pulse (of

about 1 millisecond duration) when this difference changes sign in a particular direction (e.g. from positive to negative). The direction of piston movement for which a pulse is produced is determined by switch 53, which actuates a relay in the multivibrator 52 so as to select which monostable multivibrator input is used to sense the output of the comparator 50 (i.e. the one triggered on rising or falling edges). The pulse produced by multivibrator 52 causes a sample-and-hold amplifier 54 to measure the quotient signal for the duration of the former (i.e. about 1 millisecond). A digital panel meter measures the output of the sample-and-hold amplifier 54, and changes reading only when a new measurement is made. The quotient of the solenoid current and piston speed signals (both of which are produced by the arrangement shown in Fig. 2) is evaluated by an analog divider 55. An absolute value conversion circuit 56 immediately precedes the divider numerator input because the absolute value of the denominator (piston speed) has already been taken. The signal which corresponds to the absolute value of the piston speed is used (rather than that corresponding to the piston speed itself) because in the present case the divider denominator input only accepts positive voltages. Hence, in order to obtain a positive value for the quotient, the absolute value of the numerator is also taken. The switch 53 actuates a relay in a voltage reference 57, which determines the constant voltage to be added to the solenoid current signal by a summing and buffer amplifier 58.

In the present implementation of the above arrangement, all measurement, computation and control tasks are carried out by analog electronics, although they could be done using a digital scheme.

In order to allow the above arrangement to make sensible measurements of the purifier flow resistance, it may of course be necessary to bypass particle filters, or any other significant flow resistances in the purification

loop. Note that the scheme also makes it relatively easy to determine the status of such filters, so that they may be either replaced or cleaned.

CLAIMS

1. A magnetically-driven clearance-sealed piston pump for pumping high purity gases at high pressures, the pump comprising:

a piston having a permanent magnetic member; and,

a cylinder of non-ferromagnetic material in which the piston reciprocally moves;

the cylinder wall and piston being composed of a metal or metals having at least some hexagonal close packed structure at least at the surface of said cylinder wall and piston, the coefficient of friction of said metals being less than substantially 0.9 in air, inert gas, or ultrahigh vacuum environments.

2. A pump according to claim 1, wherein at least one of the piston and the cylinder wall is made of an alloy having a composition of substantially 9-11% Ni, 19-21% Cr, 14-16% W, 0-3% Fe, 0.05-0.15% C, 0-1% Si, 1-2% Mn, 0-0.03% P, 0-0.03% S, and balance Co.

3. A magnetically-driven clearance-sealed piston pump for pumping high purity gases at high pressures, the pump comprising:

a piston having a permanent magnetic member; and,

a cylinder of non-ferromagnetic material in which the piston reciprocally moves;

at least one of the piston and the cylinder wall being made of an alloy having a composition of substantially 9-11% Ni, 19-21% Cr, 14-16% W, 0-3% Fe, 0.05-0.15% C, 0-1% Si, 1-2% Mn, 0-0.03% P, 0-0.03% S, and balance Co.

4. A pump according to any of claims 1 to 3, wherein the cylinder wall has at least one circumferential pressure-equalising groove.

5. A magnetically-driven clearance-sealed piston pump for pumping high purity gases at high pressures, the pump comprising:

a piston having a permanent magnetic member; and,

a cylinder of non-ferromagnetic material in which the piston reciprocally moves;

the cylinder wall having at least one circumferential pressure-equalising groove.

6. A pump according to claim 5, wherein at least one of the piston and the cylinder wall is made of an alloy having a composition of substantially 9-11% Ni, 19-21% Cr, 14-16% W, 0-3% Fe, 0.05-0.15% C, 0-1% Si, 1-2% Mn, 0-0.03% P, 0-0.03% S, and balance Co.

7. A pump according to any of claims 1 to 6, wherein the clearance gap between the piston side wall and the cylinder is less than substantially 0.023mm.

8. A pump according to claim 7, wherein the clearance gap between the piston side wall and the cylinder is less than substantially 0.011mm.

9. A pump according to claim 8, wherein the clearance gap is substantially 0.005 mm or less.

10. A pump according to any of claims 1 to 9, wherein the piston has at least one circumferential pressure-equalising groove.

11. A pump according to any of claims 1 to 10, wherein the stroke of the piston is at least twice the working length of the piston.

12. A pump according to any of claims 1 to 11, wherein the working surface of at least one of the cylinder wall and piston is mechanically polished.

13. A pump according to any of claims 1 to 12, wherein the magnetic member is a rare earth-cobalt alloy.

14. A pump according to claim 13, wherein the magnetic member is a samarium-cobalt alloy.

15. A method of controlling and monitoring movement of a movable permanent magnetic member which moves under the influence of a variable magnetic field, the method comprising the steps of:

measuring the instantaneous total magnetic field produced by the movable magnetic member and the variable magnetic field and producing a first output signal;

determining the instantaneous value of the variable magnetic field and producing a second output signal;

subtracting said second output signal from said first output signal to produce a third output signal which is dependent substantially only on the position of the movable magnetic member relative to the sensor; and,

controlling the variable magnetic field according to the third output signal.

16. A method according to claim 15, wherein the permanent magnetic member produces a magnetic field having a magnitude varying proportionally to r^{-3} where r is the distance from the permanent magnetic member, said third output signal being operated on to produce a linear signal indicative of the position of the permanent magnetic member in accordance with said inverse cube dependency.

17. A method according to claim 15 or claim 16, applied to a pump according to any of claims 1 to 14.

18. A method according to claim 17, comprising the step of determining a signal representative of the current in a solenoid which produces said variable magnetic field at a predetermined piston position, said signal providing an

indication of pressure drop across the pump thereby to provide an indication of the state of components through which the gas must be moved.

19. A method according to claim 17, comprising the step of determining the quotient of piston speed and a signal representative of the current in a solenoid which produces said variable magnetic field at a predetermined piston position, said quotient providing an indication of flow resistance encountered by the pump thereby to provide an indication of the state of components through which the gas must be moved.

20. A method according to claim 18 or claim 19, wherein the signal representative of the solenoid current is obtained by adding a constant to a solenoid current signal.

21. A control system for controlling and monitoring movement of a movable permanent magnetic member which moves under the influence of a variable magnetic field, the system comprising:

a sensor for measuring the instantaneous total magnetic field produced by the movable magnetic member and the variable magnetic field and producing a first output signal;

means for determining the instantaneous value of the variable magnetic field and producing a second output signal;

means for subtracting said second output signal from said first output signal to produce a third output signal which is dependent substantially only on the position of the movable magnetic member relative to the sensor; and,

means for controlling the variable magnetic field according to the third output signal.

22. A system according to claim 21, further comprising a movable permanent magnetic member composed of a rare earth-cobalt alloy.

23. A system according to claim 22, wherein the permanent magnetic member is composed of a samarium-cobalt alloy.

24. A system according to claim 22 or claim 23, further comprising a solenoid for producing the variable magnetic field, the solenoid having an air core.

25. A system according to any of claims 22 to 24, further including a pump according to any of claims 1 to 14.

26. A magnetically-driven clearance-sealed piston pump substantially as described with reference to the accompanying drawings.

27. A method of controlling and monitoring movement of a movable magnetic member which moves under the influence of a variable magnetic field, substantially as described with reference to the accompanying drawings.

28. A control system for controlling and monitoring movement of a movable permanent magnetic member which moves under the influence of a variable magnetic field, substantially as described with reference to the accompanying drawings.

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Fxaminer's report to the Comptroller under Section 17
(.e Search report) -35-

Relevant Technical Fields (i) UK Cl (Ed.M) F1W (WCK) (ii) Int Cl (Ed.5) F04B 17/00, 17/04; 35/00, 35/04	Application number GB 9410422.1 Search Examiner C J DUFF Date of completion of Search 3 AUGUST 1994
Databases (see below) (i) UK Patent Office collections of GB, EP, WO and US patent specifications. (ii) ON-LINE DATABASES: WPI, CLAIMS, JAPIO	Documents considered relevant following a search in respect of Claims :- 1-4, 7-14, 26

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Category	Identity of document and relevant passages		Relevant to claim(s)
A	GB 2241991 A	(NITTO KOHKI)	1, 3
A	GB 2241287 A	(NITTO KOHKI)	1, 3
A	GB 882965	(CHAUSSON)	1, 3
A	US 4671745	(SMITH)	1, 3
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